Renewable and Sustainable Energy Reviews 15 (2011) 3019–3028

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Particulate matter emissions from combustion of wood in district heating applications

S. Ghafghazi[a], T. Sowlati[a,*], S. Sokhansanj[b,c], X. Bi[b], S. Melin[d]

[a] Department of Wood Science, University of British Columbia, 2931 – 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada
[b] Department of Chemical & Biological Engineering, University of British Columbia, 2360 East Mall, Vancouver, BC V6T 1Z3, Canada
[c] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, United States
[d] Delta Research Corporation, Delta, BC, Canada

ARTICLE INFO

Article history:
Received 28 June 2010
Accepted 24 March 2011

Keywords:
Wood biomass
Particulate matter emissions
Dioxin and furan
District energy systems
Biomass combustion systems
Flue gas cleaning systems

ABSTRACT

The utilization of wood biomass to generate district heat and power in communities that have access to this energy source is increasing. In this paper the effect of wood fuel properties, combustion condition, and flue gas cleaning system on variation in the amount and formation of particles in the flue gas of typical district heating wood boilers are discussed based on the literature survey. Direct measurements of particulate matter (PM) emissions from wood boilers with district heating applications are reviewed and presented. Finally, recommendations are given regarding the selection of wood fuel, combustion system condition, and flue gas cleaning system in district heating systems in order to meet stringent air quality standards. It is concluded that utilization of high quality wood fuel, such as wood pellets produced from natural, uncontaminated stem wood, would generate the least PM emissions compared to other wood fuel types. Particulate matter emissions from grate burners equipped with electrostatic precipitators when using wood pellets can be well below stringent regulatory emission limit such as particulate emission limit of Metro Vancouver, Canada.

Contents

1. Introduction

Recent efforts towards reducing greenhouse gas emissions have led many countries to utilize renewable energy sources for heat and power generation purposes. Among renewable sources, wood

* Corresponding author. Tel.: +1 604 822 6109.
E-mail address: taraneh.sowlati@ubc.ca (T. Sowlati).

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doi:10.1016/j.rser.2011.04.001

biomass is considered as a greenhouse gas neutral energy source; therefore governments have been implementing policy measures to increase the share of wood biomass in their countries' primary energy source basket.

In countries where abundant sources of biomass are available, producing all or part of energy requirements of communities from biomass is now a well established concept. Sweden is a good example among countries with established market for utilizing various forms of wood biomass in community heat and power applications [1]. Despite its wide application, there are concerns about potential negative human health impacts of certain pollutants concentration in the air from combustion of wood fuel for energy generation in populated areas.

Scientific evidences show that human exposure to airborne particulate matter emissions can have far severe health implications than many other airborne pollutants [2]. Samet et al. [3] found correlation between the level of PM_{10} concentration in the ambient air and the rate of death. Pope et al. [4] concluded that long-term exposure to fine particulate matter from combustion would have approximately a 6% and 8% increased risk of cardiopulmonary and lung cancer mortality, respectively. Exposure to ultra-fine particulates (0.01–2.5 μm – PM_{25}) could increase the risk of severe respiratory disease [5]. Also, the chemical composition of particles influences the severity and type of health effects.

Uncontrolled wood combustion will emit a variety of air pollutants to the atmosphere [6]. Van Loo and Koppejan [7] list primary emissions of wood combustion as: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non methane volatile organic compounds (NMOC), nitrogen oxides (NO_x) and nitrous oxide (N_2O), ammonia (NH_2), sulphur oxides (SO_x), particulate matters (PM), trace elements of heavy metals, dioxins and furans-polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Concerns with wood combustion for community energy generation in a populated area are mostly related to particulates found in the flue gas [8]. Among the toxic chemical compounds that can be found in the combustion of material with chlorine content are dioxins and furans. Dioxins and furans are among ultra-fine particles (below 1 μm in diameter) emitted to the atmosphere from wood combustion. Dioxins and furans in air, water, soil and food causes negative health effects, such as carcinogenicity, immunotoxicity, and disturbance of lipid metabolism in humans [9]. It has been consistently observed that human exposure to dioxins and furans increases the mortality rate in all cancer types including rectal and lung cancers [10]. Negative effects on endocrine and reproductive system are among the most sensitive effects of dioxins and furans [11]. Trace elements of metals, such as sodium, potassium, cadmium, lead, mercury, and arsenic that can be found in the wood combustion flue gas particles in very small amounts have toxic effects on human [8]. Therefore, monitoring and controlling both concentration and composition of particulate matters in the air should be of the highest importance for municipal authorities [8].

Usually each regional district has regulatory emission limits in place for point source emitters in order to maintain the desirable local air quality. In 2008, Metro Vancouver introduced air contaminant discharge bylaw within the region. The regulations divided the boiler and heat producing systems into three categories of small (<3 MW), medium (3–50 MW) and larger than 50 MW systems. This regulation, sets the maximum total filterable particulate matter emission at 18 mg/m^3 (at 20 °C, 101.325 kPa, dry gas, and 8% O_2).[1] For rural applications, the maximum particulate matter is set at 30 mg/m^3. An urban facility is defined as a boiler or heater operating within 500 m of more than 20 residential or business premises, schools, hospitals, and such a like. The regulation sets the limits for nitrogen oxides at120 mg/m^3, and carbon monoxide at120 mg/m^3 for new or modified systems and 200 mg/m^3 for the existing boilers [12]. This regulation defines wood products as wood pellets, hog fuel, mill ends, wood chips, bark, shavings or sawdust and industrial residue of wood that has not been treated with glue, paint and preservative, or do not contain foreign substances harmful to humans, animals or plants when combusted (e.g. salt laden wood). Composition of particulates is highly important when considering human toxicity effects of airborne pollutants [13]. Most regulations impose limits on mass concentration measures of particulate emissions regardless of their specific chemical composition.

The primary aim of this study is to provide measured ranges of particulate emissions from the literature on systems that can typically be used for district heating applications. The secondary objective is to provide insight into factors influencing particulate matter emission levels from typical size district heating systems (from ∼500 kW to ∼10 MW) utilizing wood combustion. Special attention is paid to the effects that combustion condition and natural variations of wood composition would have on the particulate matter emission levels from wood combustion.

2. Particulate matters from wood combustion

Primary particulate emissions from wood combustion are from two main sources: (1) particulates from complete combustion including inorganic material in the flying ash, and (2) particulates from incomplete combustion including soot, condensable organic particles (tar), and char [14].

It has been reportedly shown that particulate mass concentration in the flue gas of complete wood combustion has two distribution peaks (coarse peak and fine peak) [15–18]. Sub-micron flying ash particles (<0.5 μm) are produced from vaporization of easily volatilized ash components (S, Cl, Na, and K) and the heavy metal zinc [19]. Coarse particles are formed from residual flying ash particles ejected mechanically from the fuel bed and are carried by the flue gas upwards [19] or intractable ash compounds of Ca, Mg, Si (if present) [20].

Incomplete combustion is a result of unfavorable combustion conditions such as inadequate mixing of air and fuel in the combustion chamber, low combustion temperatures, or short residence times [7]. Under incomplete combustion, submicron organic particles (soot <0.5 μm) can be produced [19]. Boman et al. [15] tested 6 different pellet fuel types in three different commercial pellet burners (10–15 kW) and observed that ultra-fine particles (<1 μm) constitute 89.5% ± 7.4% of total PM emissions from the systems, 28–92% of which were products of incomplete combustion. Advanced industrial wood combustion technologies which are available today can achieve more complete burnout of wood fuel and produce less incomplete combustion emissions compared to small scale and old type burners through maintaining desirable combustion condition [7]. Wood fuel properties [21] and combustion technology [22] affect composition as well as amount of particulate matter emissions leaving the combustion chamber.

2.1. Wood properties and particulate emissions

The European Standardization Committee for solid biofuels (CEN/TC 335) defines the quality of wood biomass by its physical properties and chemical content. Physical properties of wood biomass include moisture content, density, calorific value, ash content, and volatile matter content. The elemental content of wood biomass consists of C, H, N, S and Cl, water soluble Cl, Na and K con-

[1] Mass concentration of particulate emissions in the flue gas is stated in mg/m^3 with the reference condition (temperature and pressure). The mg/N m^3 unit represents mass concentration under normal gas condition (0 °C, 101.325 kPa).

tent, major elements (Al, Si, K, Na, Ca, Mg, Fe, P and Ti) content, and minor elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V and Zn) [23]. These chemical and physical properties (referred to as wood fuel quality), either directly or through affecting the combustion condition, affect the content and/or amount of combustion emissions [7].

2.1.1. Moisture content

Moisture content of wood fuel influences the net calorific value of the fuel, combustion temperature and combustion efficiency [21]. The first step in biomass combustion starts with the drying phase, in which water content of the fuel vaporizes. The amount of energy required in this phase is lower for fuels with low moisture content compared to that for fuels with high moisture content [24], thus the combustion temperature for low moisture content fuels would be higher leading to a complete burnout. Moisture content of wood pellets is in the range of 4–10% (w.b.), while the moisture content of undried green wood is as high as 50% [25]. It is very difficult to maintain a continuous combustion for wood fuel with more than 60% moisture content since the energy required to vaporize the moisture in wood exceeds the energy produced by the dry part of the wood [7].

2.1.2. Ash content

Ash content (or inorganic materials) and insoluble compounds act as a heat sink in the same way as moisture and results in lower combustion efficiency [26]. Apart from decreased combustion efficiency and higher chance of forming coarse flying ashes in the flue gas, using ash rich wood fuels such as bark and solid forest residues in wood burners cause operational problems such as sintering and formation of hard deposits in the furnaces and boilers [27].

High ash content in the wood fuel stems from natural variations in raw material, existence of mineral impurities, chemical/biological additives [21], and/or microbial growth during storage [28]. European standard for solid biofuels considers contamination with soil and sand, high content of bark, use of inorganic additives, chemical treatments such as paint, and preservation as general sources of higher ash content in pellets [23].

Chemical content of Cl, S, major elements (Al, Si, K, Na, Ca, Mg, Fe, P and Ti) content, and minor elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V and Zn) in the wood fuel form the ash components of wood fuels which directly affect aerosol and fly ash formation during wood fuel combustion [29].

2.1.3. Chlorine content

Chlorine content plays an important role in forming alkali metal chlorides, releasing the ash forming elements to the gas phase which leads to fine particulate formation [30]. Chlorine compounds are among dominant chemical compositions in the aerosol rang of particulate emissions from wood combusting district heating systems [14,17,20].

Chlorine content of fuel translates to possibility of dioxin and furan emission formation during combustion [31]. The dioxin and furan emissions from wood combustion are due to the presence of phenols and lignin or particulate carbon and chlorine [32]. Combustion of uncoated natural wood produces significantly lower amounts of dioxin and furan emission than other fuel types such as straw, coal and sewage sludge [33]; this is due to very low natural content of chlorine element in the white wood [34]. On the other hand, during wood combustion, dioxin and furan compounds are more often bound to the surface and carried away by fly ash particles. This portion of dioxin and furan emissions in the flue gas can effectively be reduced by primary and secondary emission control measures such as utilizing high quality wood fuel, optimal combustion condition, and fly ash precipitation at low temperatures (<200 °C) [37]. Lavric et al. [35] reviewed studies which aimed at measuring and characterizing dioxin emissions from wood combustion. They concluded that combustion condition (combustion technology, operating condition, and load condition) and fuel properties (size distribution, shape, moisture and ash contents, and ash melting behavior) are the most influential parameters on the level of dioxin emissions. Table 1 shows the reported dioxin levels from wood combustion technologies that are in the size ranges suitable for district energy applications (from ~500 kW to ~10 MW). Uncontaminated natural wood combustion in small and medium sized modern plants with flue gas cleaning systems, under good burnout condition, will produce dioxin emission levels well below the health risk limit of 0.1 ng I−TEQ/m^3 [35].[2]

2.1.4. Sulphur content

Sulphur content of wood fuel, reacts with alkali metal chlorides and hydroxides during the combustion process through sulphation reactions. The nucleation and condensation temperatures of alkali metal sulphates are higher than that of chlorides so less volatile sulphates are formed [30]. It has been reported that sulphur decreases the release of chlorine, therefore induced fine mode particles in biomass combustion [36,37]. Nonetheless, S content negatively affects release of Cl and formation of corrosive compounds such as $FeCl_2$ or $ZnCl_2$ at lower temperatures during wood combustion [29]. Potassium sulphate is generated in small amounts during wood combustion and has been observed as a dominant compound in the aerosol range fly-ash of wood combustion [14,38,39].

2.1.5. Major and minor elements

During the devolatilization period of biomass combustion when volatile contents of biomass vaporize, inorganic elements of biomass including Na, K, Mg, Al, and Ca are retained within the biomass char. After the devolatilization process, vaporization of monovalent metals of Na and K takes place, while divalent and trivalent metals of Mg, Al, and Ca are more highly retained in biomass chars [40]. The main ash-forming elements found in the fly-ash of wood combustion (besides Cl and S) include K, Na, Zn, Pb, Cd, Cr, and Mg [29]. Fig. 1 shows the general mechanisms leading to coarse and fine mode formation of particle emissions in a fixed-bed combustor from major and minor ash-forming elements present in untreated wood.

Compositional analysis of the flue gas of district heating systems operating on wood fuels has shown that refractory species such as Ca and Mg as well as small amounts of Si, P, Fe and Mn (from low quality wood fuels such as forest residues) are dominant in the coarse mode [17,20,38,39]. Vaporized compounds of alkali metals (K and Na) are dominantly present in the fine mode [14,38,39,41]. Smaller amounts of these species observed in the coarse mode of wood burning district heating systems flue gas [17] are resulted from bounding of these volatile compounds [29]. Heavy metal traces of Cd, Zn, Cr, [17,20,38,42,43] as well as Pb, Hg, As, Cu [43] are dominantly present in the vaporized form and the aerosol mode [29] of wood combustion flue gas from district heating systems.

Table 2 shows key physical properties and chemical composition of uncontaminated, natural, solid softwood fuels.

As it can be seen in the table, wood fuels obtained from softwood stem (wood pellet, wood chips and sawdust) contain very low amounts of alkali metals and dioxin, furan, and fine particle forming elements; while these amounts are much higher in other parts of

[2] *I-TEQ:* International Toxicity Equivalent factor initially set by North Atlantic Treaty Organization (NATO) in 1989 expresses the toxicity level of a mixture of toxics as a single number. *I-TEQ* equals the level of toxicity of the mixture of toxics to that of 2,3,7,8-TCDD (tetrachlorinated dibenzo-p-dioxin) which is the reference compound.

Table 1
Dioxin levels from wood fuel combustion in small and medium sized burners.

Combustor type/application	Wood fuel type	Gas cleaning system	Dioxin emission, ng I–TEQ/dscm at 11% O_2
Moving grate (2 MW)	Bark chips	N/A	0.019
Moving grate (16 MW)	Bark chips	N/A	0.006
Wood dust burner (9.6 MW)	Pine chips	N/A	0.004–0.006
Grate burner (11 MW)	Wood chips	ESP	0.007
Grate burner (1 MW)	Wood chips	Cyclone, bag filter	0.050
Grate burner (0.6 MW)	Wood chips	Cyclone, ESP	0.039
Moving grate (13.8 MW)	Pine wood	Multi-cyclone	0.0783
Moving grate (6.3 MW)	Wood chips	N/A	0.0027
Grate firing (850 kW)	Waste wood chips from demolition	Cyclone/fabric filter	2.7
Grate firing (1.8 MW)	Waste wood chips from demolition	Cyclone/ESP	9.57
Moving grate (850 kW)	Urban waste wood	Cyclone/cloth filter (Ca/C)	2.04
Bubbling fluidized bed (4 MW)	Wood chips/15–45% RDF	ESP	<0.1
Fluidized bed (12 MW)	Urban waste wood	N/A	0.1
Circulating fluidized bed (17.5 MW)	Urban waste wood	Cyclone/ESP	0.71–0.73

(Source: [35]).

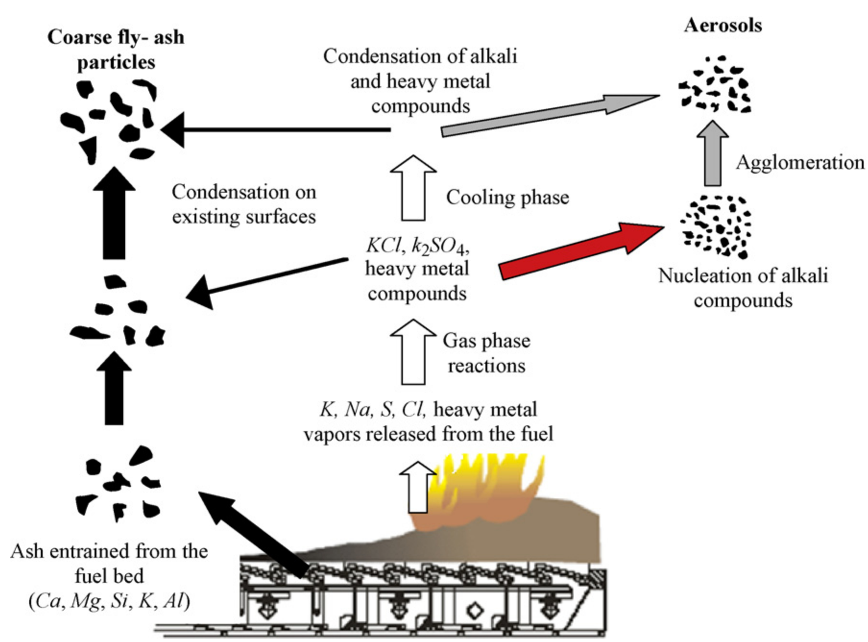

Fig. 1. Aerosol formation during fixed bed combustion of untreated wood (source: [17]).

Table 2
Physical and chemical properties of uncontaminated, natural, solid softwood fuels.

Parameter	Unit	Wood pellet	Wood chips	Sawdust	Bark	Logging residues
Moisture	wt% (w.b.)	7	50	50	50	50
Ash	wt% (d.b.)	<0.5	0.3	0.3	4	2
Bulk density	kg/m^3 (w.b.)	591	350	240	320	<350
Cl	wt% (daf)	0.005	0.01	0.01	0.02	0.01
S	wt% (daf)	0.027	0.02	0.02	0.1	0.04
K	mg/kg (d.b.)	493	400	400	2000	2000
Na	mg/kg (d.b.)	20	20	20	300	200
Cd	mg/kg (d.b.)	0.14	0.1	0.1	0.5	0.2
Zn	mg/kg (d.b.)	13.2	10	10	100	<100
Pb	mg/kg (d.b.)	0.43	2	2	4	3
Cr	mg/kg (d.b.)	0.6	1	1	5	<5
Cu	mg/kg (d.b.)	1.1	2	2	5	<5
Ca	mg/kg (d.b.)	900	900	900	5000	5000
Mg	mg/kg (d.b.)	150	150	150	1000	800
Mn	mg/kg (d.b.)	147	147	147	500	251
Hg	mg/kg (d.b.)	0.02	0.02	0.02	0.05	0.03
As	mg/kg (d.b.)	<0.1	<0.1	<0.1	1	0.3
P	mg/kg (d.b.)	60	60	60	400	500

(Source: [21,25,29]).
Wood pellet values are from direct measurement study [21] when different than stem wood value estimates.

the tree such as bark and mixed logging residues [29]. Most importantly natural content of Cl in the softwood stem is well below the guiding concentration of 0.1 wt% (d.b.) associated with the dioxin and furans emissions. In processed wood, higher Cl, S, K, and Na content can also be an indication of organic or inorganic additives (such as insecticides, adhesives, glues, lacquer, dyestuff, or wood preservatives) in the raw material [21], higher content of bark than specified, and/or contamination during storage/transportation by salt water, road salting, and preservation chemicals [23]. Higher content of Si or Na in the wood fuels than wood natural content can be related to mineral impurities such as sand or glass during handling and processing [21].

2.2. Biomass combustion systems

Different combustion technologies without utilizing high efficiency flue gas particulate abatement equipment yield various amounts of particulate matter emissions ranging between 60 and 2100 mg/N m^3 [14]. With the introduction of improved biomass combustors in the past two decades, higher combustion efficiencies and lower emissions are now observed from these systems compared to old-type wood burning boilers [22].

Biomass combustion systems are available in sizes ranging from a few kW up to more than 100 MW. Below 100 kW$_{th}$ systems are usually referred to as small-scaled systems [29]. Medium and large scaled combustion technologies used to produce heat from biomass include: (1) grate stoker burners, (2) fluidized bed combustors, (3) suspension burners, and (4) two-stage gasification-combustion systems [7,25,26,29,44].

In grate stoker burners, a stoker spreads wood biomass on a stationary sloping, vibrating, or moving grate on which combustion takes place [44]. In these burners, the grate is responsible for lengthwise transport of fuel and distribution of the primary air. Grate burners with moving grates (traveling, reciprocating, and vibrating) have more control over burning process, more complete burnout, less organic emissions, and higher overall efficiencies compared to those with stationary grates [45]. Among moving grates, vibrating grates [46] have less moving parts compared to traveling [47] and reciprocating [46] grates, therefore their operating and maintenance costs are lower than those of traveling and reciprocating burners.

Fluidized bed boilers are complex and capital intensive technologies [48] that are usually attractive for plants over 20 MW$_{th}$ capacity [7]. In fluidized bed combustion systems, biomass is introduced to a suspension bed of hot and inert granular material (fluidized bed) [7]. The main types of fluidized bed are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) [44]. Ultrafine particle emissions of tar and aerosols sourcing from incomplete combustion are negligible in fluidized bed combustors as a result of more homogeneous temperature in the combustion bed. However, the amount of macro particles of fly ash, dust and unburned carbon entrained in the flue gas from the combustion bed is high [38]. Circulating fluidized bed captures the unburnt carbon in the flue gas and returns it to the combustion bed for complete burnout. However, the level of macro particulate emissions from combustion systems fired with low-ash biomass fuels is expected to be negligible [49].

In suspension burners, fine particles of pulverized wood are pneumatically injected into the furnace [7] where combustion takes place. In suspension burners three steps under controlled staged-air circumstances can be recognized: (1) devolatilization to char and volatiles, (2) combustion of the volatiles, and (3) combustion of the char [50]. Suspension burners may be designed to handle different fuel types in various modes of solid, liquid, or gas. Examples include co-firing of biomass with coal in pulverized burners [51] or co-combustion of biomass in natural gas fired furnaces [52]. Controlled range of wood powder particle size (<2 mm) [53] and low moisture content of fuel (less than 15%) [44] are two key parameters leading to complete burnout of fuel and therefore low emissions in the suspension burners. Direct burning of pulverized biomass in suspension burners has limited applications mainly due to the extensive fuel preparation requirement [44,54]. Particulates in the fly ash of biomass suspension firing is considerably higher than grate and fluidized burning methods since in this method, major parts of the particulates will end up in the fly ash. There are also problems associated with higher amount of NO_x emissions from this type of biomass combustion because of difficulties in staging of the combustion process in such burners [55]. Extensive literature on application of pulverized burners for co-firing of coal with biomass is available [56,50], though studies aiming at characterization and direct measurement of particulate emissions from biomass burning in such burners could not be found.

The two-stage gasification-combustion is based on the gasification reaction. At first, under partial oxidation condition at high temperatures, a combustible gas mixture called syngas would be generated from biomass. This gas mixture which has relatively low calorific value can be burnt directly in an oxidizer attached to a boiler for hot water or steam generation [57]. Direct combustion of the produced syngas from gasification process in an oxidizer or a boiler for heat generation purposes is a rare application of this technology [58]. Two-stage combustion technologies have been commonly practiced in the industry to control CO and NO_x emissions. The syngas in this case is not a product but an intermediate in the combustor. Syngas produced from biomass gasification contains high amounts of tar, char, and other particulates which are a major issue for direct utilization of this gas in turbines and engines [59,60]. Published material reporting the amount of particulates and emissions in the flue gas after direct combustion of treated/untreated syngas is not available.

2.3. Flue gas cleaning systems

In order to reduce emissions of particulate matters from biomass combustion usually flue gas cleaning equipment is used. Major flue gas cleaning systems applied in wood combustion applications include: (1) cyclones, (2) electrostatic precipitators, and (3) baghouses [7].

2.3.1. Cyclones

Cyclones use centrifugal forces to separate dust and solid particles from gas and are widely used in the industry [7]. Separation efficiency of cyclones is higher for coarse particles. Finer particles (<10 μm) exit at the top of the cyclone with the flue gas [61]. Separation efficiency of cyclones is around 85% for PM_{10} and decreases to below 20% for particulates with less than 5 μm aerodynamic diameter [62]. There has been extensive effort to increase separation efficiency of cyclones [63], yet, cyclone separators are most often used for the primary dust collection purposes [64] downstream of which a more efficient emission control system like an electrostatic precipitator or a baghouse is used.

2.3.2. Electrostatic precipitators

Electrostatic precipitators (ESP) electrically charge the suspended particles in the flue gas and then attract them to an electrode plate from where they can be removed [7].

The overall collection efficiency of ESP systems in terms of mass volume (mg/N m^3) is more than 99%. Nonetheless, overall collection efficiency of ESPs in terms of particle numbers (number of particles/N m^3) might be as low as 50% since sub-micron particles are very likely to escape the electrical fields [65]. Improved ESP systems have been reported to clean the ultra-fine particles from combustion flue gas with efficiencies in the range of 95%. An improvement

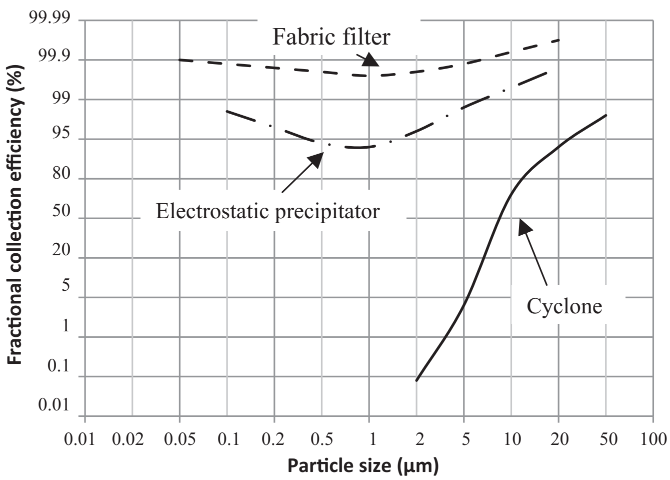

Fig. 2. Collection efficiency of conventional gas cleaning technologies (adopted from: [74]).

on ESP of a pulverized coal burning facility increased the collection efficiency of unburnt carbon particles or fly ash in the diameter range of 0.06–12 μm to 98% [66]. Yoo et al. [67] tested a two-stage parallel-plate ESP in the laboratory on very fine NaCl, fly ash and aerosol particles between 0.03 and 0.2 μm diameter. The collection efficiency of this system was reported at 93–98%. Strand et al. [20] observed a collection efficiency of 82.7% for an ESP system on sub-micron particles (<0.8 μm). The same measurements for particles between 0.8 and 6 μm showed that ESP collection efficiency was 95.6% for course particles. Lind et al. [68] reported a total collection efficiency of 99.2–99.8% for an ESP installed after a 66 MW biomass-fueled bubbling fluidized bed. For particles in the size range of 0.1–2 μm, the collection efficiency of the ESP was 96–97%.

2.3.3. Baghouses

In baghouse systems, the suspended particulates in the combustion flue gas are collected on the surface of a sieving textile media (fabric filter) [7]. Baghouses are economical and effective systems that are widely used for industrial emission control [69]. A baghouse, if designed properly, is able to remove multiple pollutants such as particles, heavy metals, dioxins and furans from the flue gas [70]. Ergüdenler et al. [71] observed dust and particle collection efficiencies well above 99.5% from baghouses with high temperature resistant ceramic filters applied to flue gas stream generated in the laboratory. Also, trace element collection efficiency of a baghouse on a pulverized coal boiler was reported over 95% for particles as small as 0.08 μm [72]. Collection efficiency of baghouse filter systems depends to a great extent on key design parameters such as the choice of filter fabric and air-to-cloth ratio [73]. An overview of baghouse cleaning systems is given in [73].

Fig. 2 shows the collection efficiency range of conventional gas cleaning systems. As it can be seen from this figure, fabric filters and electrostatic precipitators have high collection efficiency well above 95% at sub-micron particle ranges. The reason for the "U" shaped collection efficiency curve of ESP systems has been explained by the decreased charge of smaller size particles until this effect is offset by the increasing mobility property of ultra-small particles (due to reduced drag force) [75]. More detailed review of cleaning technologies, especially ESP systems that have vast applications for wood combustion flue gas cleaning can be found in [76].

3. Discussion

In order to estimate particulate emissions from wood combustion in district heating systems, US EPA emission factors for particulate emissions from wood residue combustion [77] can be used. However, this source provides very limited information about the properties of wood fuel or type and size of the combustion technology in use that influence particulate emission levels from various systems. Many studies have been focusing on direct measurement and characterization of particulate emissions from wood burning district energy systems in order to quantify and explain the levels and parameters affecting the formation of air pollutants.

Table 3 summarizes the particulate emission levels reported from literature studying various wood fuels and combustion systems used in district heating system applications in terms of technology type and size. Studies in Table 3 are sorted out based on the fuel type and then combustion system.

Combustion of high quality wood pellets derived from natural stem wood in grate boiler district heating systems (1.5–2.5 MW) produces particulate emissions between 50 and 100 mg/m^3 (20 °C, 101.325 kPa, dry gas and 8% O_2) downstream of a multi-cyclone [14,39,42,78]. These studies also extended their analyses to include the effect of varying fuel properties, fuel load, and excess air ratio on emission levels. Some as well included compositional analysis of the particles. In district heating wood pellet grate boilers, increase in excess air would not increase the mass concentration of particles in the flue gas [14,42,78]. However, decrease in the load and excess air would shift the particle sizes towards larger particles due to increase in soot formation and agglomeration of these particles [14,78]. In the sub-micron range also inorganic elements of potassium, sulphur, and chlorine were dominant with small amounts of sodium, magnesium, and zinc [14,39,78]. Johansson et al. [78] found that utilizing wood pellets with lower density than the standard value increases the amount of CO and unburnt carbon as well as particles mass concentration in the flue gas. Easier disintegration of low-density fuels during early stages of combustion is a possible explanation for this observation [14]. However, neither of the studies identified a clear tendency of higher number concentration of particles when lower density wood pellets were used [14,78]. Mass concentration of particulate emissions from wood briquette combustion in district heating grate boiler is very well comparable to the wood pellets boilers [78]. In this case, the increase in mass concentration of particles in the flue gas is notably higher when excess air increases compared to the case of wood pellets [14,78]. Also using low density briquettes would increase the number concentration of particles in the flue gas [78].

Utilization of dry wood material (shavings, sawdust, and wood chips) with moisture content below 10 wt% in a 1.5 MW moving grate boiler result in particulate emission levels comparable to wood pellets combustion under the same condition [39]. However, the mass concentration of particulate emissions from combustion of dry wood material at medium load would be almost double than the amount generated at low load (increasing load from 0.3 MW to 0.9 MW) [39].

Combustion of dry saw dust (10 wt%. moisture content) under low, medium, and high load conditions in a 1.5 MW moving grate boiler showed that increase in boiler load slightly increases the concentration of coarse mode particles in the fly ash. Also, particle emission levels from dry saw dust combustion were relatively close to the emission levels from wood pellet combustion under similar combustion conditions (results from dry saw dust combustion were about 10 mg/Nm^3, 13CO_2, higher than the case of wood pellets) [42].

Utilization of dry wood chips (moisture content ∼10 wt%) in a 440 MW moving grate boiler generates particle matter emissions much lower than that of using wet wood chips (moisture content ∼50 wt%) [17]. Obernberger et al. [17] also found the tendency of higher coarse mode fly ash formation with increasing the plant load while they could not identify such a tendency for the aerosol mode fly ash. They related this observation to higher possibility

Table 3
Particulate emission levels in the flue gas of small and medium sized wood burning systems.

Wood fuel type	Combustion system	Gas cleaning system	Particulate level	Measurement reference	Particulate level* mg/m^3	Reference
Wood pellets	Grate fired (2 MW_{th})/100% load	Multi-cyclone	50–100	mg/N m^3, at an average 7–9% O_2	57.8–99.1	[14]
Wood pellets	Grate boiler with moving scrapes (1.75 MW)/100% load	Multi-cyclone	35	mg/MJ, at measured 8.9% O_2	72.9	[78]
Wood pellets	Moving grate (1.5 MW_{th})/medium load	Multi-cyclone	51 (fly ash), 44 (<1 μm), 7 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Wood pellets	Moving grate (1.5 MW_{th})/high load	Multi-cyclone	51 (fly ash), 41 (<1 μm), 10 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Pellets	Moving grate (1.5 MW_{th})/low load (0.3 MW)	Multi-cyclone	59	mg/N m^3, at 13% CO_2	53.1	[39]
Wood briquettes	Grate boiler with moving scrapes (2.5 MW)	Cyclones	40	mg/MJ, at measured 5.7% O_2	85	[78]
Dry wood (shaving, sawdust, wood chips)	Moving grate (1.5 MW_{th})/low load (0.3 MW)	Multi-cyclone	48	mg/N m^3, at 13% CO_2	49.2	[39]
Dry wood (shaving, sawdust, wood chips)	Moving grate (1.5 MW_{th})/medium load (0.9 MW)	Multi-cyclone	101	mg/N m^3, at 13% CO_2	104.2	[39]
Dry saw dust	Moving grate (1.5 MW_{th})/low load	Multi-cyclone	74 (fly ash), 63 (<1 μm), 11 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Dry saw dust	Moving grate (1.5 MW_{th})/medium load	Multi-cyclone	63 (fly ash), 49 (<1 μm), 14 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Dry saw dust	Moving grate (1.5 MW_{th})/high load	Multi-cyclone	64 (fly ash), 44 (<1 μm), 20 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Dry wood chips (spruce)	Water tube moving grate boiler (440 kW_{th})	None	50–100 (fly ash), 20 (<1 μm)	mg/N m^3 at 13% O_2	54–107 (fly ash), 21.5 (<1 μm)	[17]
Wet wood chips (spruce)	Water tube moving grate boiler (440 kW_{th})	None	50–200 (fly ash)	mg/N m^3 at 13% O_2	54–211 (fly ash),	
Wet wood chips	Bubbling fluidized bed (4 MW_{th}@ 90% load)	ESP	2.3	mg/N m^3 at 11% O_2	2.5	[43]
Wet forest residues	Moving grate burner (6 MW)/4.5–5 MW load	ESP	15.8 (fly ash), 13.2 (0.03–1.0 μm), 2.6 (1.0–6.8 μm)	mg/N m^3, at 13% CO_2		[20]
Wet forest residues	Moving grate burner (6 MW)/4.5–5 MW load	ESP and condenser	8.2 (fly ash), 1.8 (0.03–1.0 μm), 6.3 (1.0–6.8 μm)	mg/N m^3, at 13% CO_2		[20]
Wet forest residues	Moving grate burner (6 MW)/4.5–5 MW load	Multi-cyclone	134.9 (fly ash), 76.3 (<0.8 μm), 58.5 (0.8–6 μm)	mg/N m^3, at 13% CO_2		[20]
Forest residues	Moving grate (1 MW_{th})/medium load	Multi-cyclone	120 (fly ash), 117 (<1 μm), 3 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Forest residues	Moving grate (1 MW_{th})/high load	Multi-cyclone	185 (fly ash), 100 (<1 μm), 85 (1–5 μm)	mg/N m^3, at 13% CO_2		[42]
Wet forest residues	Moving grate boiler (1 *MW*-80% load)	Multi-cyclone	218 (fly ash), 100 (<1 μm), 118 (1–10 μm)	mg/N m^3, at 13% CO_2		[43]
Wet forest residues	Moving grate boiler (1 MW-60% load)	Multi-cyclone	150 (fly ash), 145 (<1 μm), 5.3 (1–10 μm)	mg/N m^3, at 13% CO_2		[79]
Wet forest residues	Moving grate boiler (1 MW-45% load)	Multi-cyclone	122 (fly ash), 117 (<1 μm), 5.1 (1–10 μm)	mg/N m^3, at 13% CO_2		[79]
Wet forest residues	Moving grate boiler (6 MW-85% load)	Multi-cyclone	157 (fly ash), 79 (<1 μm), 78 (1–10 μm)	mg/N m^3, at 13% CO_2		[79]
Wet forest residues	Grate boiler (1 and 6 MW)	Cyclone	25–100 (<1 μm)	mg/N m^3, O_2 or CO_2 percentage not specified		[41]

Table 3 (*Continued*)

Wood fuel type	Combustion system	Gas cleaning system	Particulate level	Measurement reference	Particulate level* mg/m^3	Reference
Wood residue	Two stage gasifier-combustor system (Cogeneration-17.5 MW_{th} and 1.38 MMe)	ESP	2.5	mg/N m^3, O_2 or CO_2 percentage not specified		[80]
80% willow/20% wood pellet	Circulating fluidized bed (3–12 MW at 8–9 MW_{th} fuel thermal effect)	Cyclone	410 (fly ash), 75 (<1 μm), 335 (>1 μm)	mg/N m^3, at an average 3.7% O_2	440 (fly ash) 80.5 (<1 μm), 359.5 (>1 μm)	[38]
Bark	Water tube moving grate boiler(440 kW_{th})	None	400–500 (fly ash), 60 (<1 μm)	mg/N m^3 at 13% O_2	429–537 (fly ash), 64.4 (<1 μm)	[17]
Waste wood	Water tube moving grate boiler (440 kW_{th})	None	300–400 (fly ash), 160 (<1 μm)	mg/N m^3 at 13% O_2	322–429 (fly ash), 171.7 (<1 μm)	[17]

*Numbers are converted to 20 °C, 101.325 kPa, dry gas and 8% O_2 concentration which is the standard condition considered in Vancouver's bylaw. The particulate emission limit in Vancouver is 18 mg/m^3. Mass balance conversion process from [7] has been used in order to convert mg/MJ unit to mg/m^3. When not stated, information about the flue gas and/or fuel composition has not been sufficient in the original paper in order to convert to the reference condition.

for ash entrainment from the fuel bed when air and fuel flow is higher. Using an ESP during the combustion of wet wood chips in a bubbling fluidized bed would reduce particulate emission levels to 2.5 mg/Nm^3, 8%O_2, far below 18 mg/Nm^3, 8%O_2 emission limit [43].

Combustion of low quality wood fuel, such as forest residues, bark, wood waste, or co-firing of willow, in moving grate boilers produces particulate emissions remarkably higher than that of wood pellets or dry saw dust and wood material [20,38,41–43,79]. Combustion of willow (co-fired with 20 wt% wood pellets) in a 12 MW circulating fluidized bed boiler with a cyclone resulted in submicron flying ashes which were mainly sulphate particles [38]. Study of fine mode particles (<1 μm) in the flue gas of moist forest residues combusted in 1 and 6 MW grate boilers downstream of cyclones was carried out by Lillieblad et al. [41]. They observed that potassium, chlorine and sulphur dominate the elemental composition of fine mode particles. They also tested the collection efficiency of an ESP cleaning system on the flue gas of moist forest residues combustion and observed a U shape collection efficiency curve with minimum on particles between 100 and 1000 nm size ranges [41]. Strand et al. [20] measured and analyzed particulate emissions downstream of an ESP flue gas cleaning system with collection efficiency of at least 96% both in the fine and coarse particle ranges on a 6 MW moving grate boiler firing wet forest residues. The main elements they found in the fine fraction of the particles were K, S, and Cl, and Zn which constituted 90% of the analyzed elements in the fine mode. In the coarse fraction of the particles Ca, Fe, and Mn were dominant (40–50% of the coarse particles mass) [20]. Due to the wood elements in low quality wood fuel, it would be difficult to limit the amount of particulate matter emissions even when a high efficiency flue gas cleaning system is used.

Grate boilers are the most commonly studied technology used in wood burning district energy systems. Operation of boilers under optimum designed condition is a key parameter in achieving controlled emission levels from biomass combustion. Reducing fuel load to levels below design range can cause higher coarse particle formation due to soot formation and higher possibility of condensation. Also, higher fuel load or higher excess air than the design range can increase the formation of coarse particles in the flue gas.

Gas cleaning systems can be utilized in order to significantly reduce the amount of particulate emissions in the wood combustion flue gas. Cyclones are widely used in district heating centers as a primary gas cleaning system to significantly reduce the amount of coarse fly ash particles. The collection efficiency of cyclones for particle diameters below 5 μm is very limited. Knowing that particle emissions from wood combustion have two dominant peaks in both coarse and fine size ranges make it necessary to use flue gas cleaning systems with high collection efficiencies in the sub-micron particle size range. Electrostatic precipitator or baghouse systems have collection efficiency in the sub-micron particle size range well above 95% which can be installed downstream from a cyclone system.

Grate burners are able to utilize a wide variety of wood fuels and moisture content range. It can be understood from Table 3 that without an efficient gas cleaning technology such as an ESP or a baghouse, grate firing of all types of wood fuel would result in PM emissions above the regulatory emission level in Vancouver, BC. Combustion of natural uncontaminated wood fuel or processed wood fuels, such as wood pellets, wood briquettes, and dry sawdust and shavings, in grate burners would result in lower amount of particulate emissions compared to that of wet wood fuel such as forest residues. For grate firing of wood pellets, installation of an ESP or a baghouse system which can reduce particulate emission levels in the flue gas under normal operation condition well above 90%, would be necessary in order to meet the 18 mg/Nm^3 regulatory limit in Vancouver, BC. Complying with the foregone regulatory limit using bark or logging residues is an issue. These materials will produce particulate emissions above 100 mg/Nm^3 and may be as high as 500 mg/Nm^3. High natural content of alkali and heavy metals in bark and logging residues results in uncontrolled vapors of toxic emissions in the fine mode of flue gas from direct combustion of these materials. Therefore, grate combustion of such material for district heating applications in populated area is not recommended.

Review of previous studies that measured the particulate matter emissions from wood burning district heating facilities revealed that limited research has been done on technologies such as suspension burner, fluidized bed and two-stage gasification technologies. These technologies have been used in wood biomass district energy systems recently. Reference [80] is an exception which is manufacturer's reported emission level from a two-stage gasification-combustion technology. Most previous studies focused on the grate firing of mixed biomass with only cyclone gas cleaning systems which is the most practiced technology in district energy centers. More research efforts are required for quantification of emission levels from alternative combustion technologies such as powder burner and gasification technologies. Although efficiency of ESP and baghouse cleaning systems have been studied widely, more studies focusing on direct measurement of particulate emissions from wood burning district heating systems that utilize these high efficiency gas cleaning systems can contribute significantly to addressing the public concern about such a practice. Also, systems to detect impregnated wood with harmful chemical and fractionate wood into suitable and unsuitable feedstock needs to be developed.

4. Conclusion

In this paper, various factors leading to formation of particulate matter emissions from combustion of solid wood biomass fuel types used in district heating applications were explained based on the literature survey. Special attention was paid to the direct measurement levels of particulate emissions and the effect of wood fuel characteristics and combustion fuel load on the formation of particulate matters.

It was concluded that wood fuel quality, which is defined by both physical properties and chemical composition, has direct impact on the formation of submicron as well as super-micron particle emissions. Utilizing high quality wood fuel is the primary consideration in order to assure limited particulate emissions especially in the submicron particle size range. High quality solid wood fuel is produced from natural stem wood raw material free of impurities such as preservatives, glue, or paint, salt, and sand, and has low moisture content. Wood fuel from non-stem wood, such as bark, contains high ash and alkali and heavy metal contents.

Among various types of available wood fuel, direct combustion of high quality wood fuel such as wood pellets produced from natural, uncontaminated stem wood generates the least amount of PM emissions both in the sub-micron and super-micron size ranges. Grate firing of wood pellets under normal operating condition would reportedly result in particle emissions in the range of about 50–100 mg/m^{-3} (20 °C, 101.325 kPa, dry gas and 8% O_2) downstream of a multi-cyclone. Cyclones are more efficient for primary dust reduction purposes in order to eliminate coarse particulates from the flue gas. Therefore, in order to meet the stringent particulate regulatory emission limit introduced in Vancouver, BC, implementation of efficient gas cleaning systems, such as ESPs or baghouses with more than 90% collection efficiency, downstream of a cyclone in wood burning district heating systems is necessary. Grate combustion of low quality wood fuels such as logging residues and bark is not recommended for district heating centers located in populated areas due to possibility of uncontrolled toxic vapors in the flue gas during combustion.

More research effort is required in order to quantify emissions from technologies such as suspension burner and two-stage gasification technology that have recently got more attention in district heating applications. Studies on direct measurement of particulate emissions from utilization of various forms of wood fuels in these technologies could not be found. The obtained information could help in building public confidence in utilization of wood biomass in such technologies.

Acknowledgement

This research was made possible through funds from British Columbia Ministry of Forests and Range and the Natural Sciences and Engineering Research Council of Canada.

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